DISCUSSION

Exploring one-dimensional compression of compacted clay under constant degree of saturation paths

G. J. BURTON*, J. A. PINEDA†, D. SHENG*, D. W. AIREY‡, F. ZHANG§, A. RAWAT||, Y. M. AL-BADRAN¶ and T. SCHANZ||

Contribution by A. Rawat, Y. M. Al-Badran and T. Schanz
Coupled hydro-mechanical properties such as degree of saturation (S_r) play an important role in the volume change response of unsaturated soils. The presented work (Burton *et al.*, 2016) is an appreciable contribution regarding the experimental procedure to describe the (one-dimensional (1D)) compression behaviour of compacted clays along constant degree of saturation paths. There are not many comparable studies on the experimental procedure relating to this topic; earlier, one of the discussion contributors, Al-Badran (2011), conducted a similar type of tests. This discussion contribution will address the issue of suction equilibration during 1D compression behaviour of compacted clays along constant degree of saturation paths. The approach proposed by Burton *et al.* (2016), rather than controlling suction, is to control the pore-water volume to keep the degree of saturation constant during the 1D compression of compacted kaolin samples. Burton *et al.* (2016) applied the vertical stress and controlled the pore-water volume simultaneously to keep the degree of saturation constant. The test results show a significant reduction in the long testing period that is normally required for unsaturated soil testing.

Al-Badran (2011) conducted similar tests on compacted Calcigel sand–bentonite mixtures (70:30). He controlled suction using an axis translation technique before applying net vertical stress incrementally because the volume change response of the soil sample due to applied vertical stress is faster than suction equilibration. Thus, as a requisite condition during the test, the degree of saturation was not allowed to exceed the targeted value. The net stress was kept constant during the suction equilibration period (1–4 weeks), and then increased slowly. After the completion of 1D compression under a particular applied net stress, the suction was adjusted in such a way that the degree of saturation remained constant during the 1D compression under the next net stress increment. The testing period required was around 4–6 weeks. Prior to this experimental study, Al-Badran (2001) presented the theoretical and practical relevance of degree of saturation using the S_r -lines concept to describe and estimate the collapse and compression curves for unsaturated soils of any initial state. As depicted in Fig. 9, a line parallel to the normal compression line (NCL) for a fully

saturated sample can be drawn for each degree of saturation. In other words, S_r -lines are the NCLs under different constant degree of saturation conditions.

The main difference between the two testing procedures (Al-Badran, 2011; Burton *et al.*, 2016) is the sequence of controlling the two parameters, namely, pore-water volume and pore volume space. The discussion contributors have some doubt that the testing period reported in Burton *et al.* (2016) is sufficient to attain the equilibration, particularly in the case of fine-grained soils such as kaolin, which is used in the study. In this regard, Fig. 10 shows the typical elapsed time plotted against water content decrease for kaolin at an applied suction of 0.05 MPa in pressure plate and osmotic tests (Tripathy *et al.*, 2014) and at an applied suction of 30 kPa and 9 MPa in osmotic tests (Baille, 2014). The reported testing period (Burton *et al.*, 2016) was approximately 48 h for test OED06 and 24 h for test OED17, while the suction changes from 100 to 300 kPa in test OED06 and 350 to 400 kPa in test OED17. In the opinion of the discussion contributors, the reported time period in Burton *et al.* (2016) should be supported by the soil-water characteristics curve data for the tested materials such as kaolin.

Al-Badran (2011) and Al-Badran & Schanz (2014) presented a model of the state surface at the yield state for unsaturated fine-grained soils; as per this model the NCLs at different degrees of saturation can be obtained by using equation (3).

$$e_{\text{uns}} = (e_{\text{NCL}} S_{\text{rc}})/(S_r)^R \quad (3)$$

where e_{NCL} is void ratio at the full saturation stage at a particular net stress level; S_{rc} is the critical degree of saturation; and R is the fitting parameter that controls the influence of the degree of saturation on the increase of the void ratio under constant net stress. Fig. 11 shows the prediction of results for 1D compression tests conducted by Al-Badran (2011).

Authors' reply

The authors thank the discussion contributors for their interest and valuable comments on this work and agree that the adopted loading rate requires careful consideration. As discussed below, the authors believe that the loading rate adopted was appropriate. The objective of Burton *et al.* (2016) was to present a novel technique for controlling the degree of saturation during laboratory testing. The authors believe that this was achieved and the technique will be of interest to those studying the coupled hydro-mechanical response of unsaturated soil.

The phenomenon of water transfer in unsaturated soils is complex due to the coupled hydro-mechanical response, and as such there is no unified criterion for establishing equilibration in unsaturated soil testing (e.g. Delage *et al.*, 2008). The water transfer process is controlled by the soil-water retention properties, which are mainly affected by

* School of Engineering, The University of Newcastle, Callaghan, NSW, Australia.

† ARC Centre of Excellence for Geotechnical Science and Engineering, School of Engineering, The University of Newcastle, Callaghan, NSW, Australia.

‡ School of Civil Engineering, University of Sydney, Sydney, NSW, Australia.

§ Department of Civil Engineering, Nagoya Institute of Technology, Nagoya, Japan.

|| Ruhr Universität, Bochum, Germany.

¶ Highway and Transportation Department, Faculty of Engineering, Al-Mustansiriyah University, Baghdad, Iraq.

Fig. 9. Typical compression curves of unsaturated soil according to the S_r -lines concept (S -lines): (a) constant water content test; (b) constant initial void ratios and different water contents; (c) constant water content and variation initial void ratios; (d) combined effect of water content and void ratio (Al-Badran, 2001)

Fig. 10. Equilibration time required for Speswhite kaolin (Baille, 2014; Tripathy *et al.*, 2014)

the initial soil state (e.g. void ratio, water content) and mineralogy. From an experimental perspective, the testing period is mainly controlled by the initial conditions, sample size and the soil type. In the reported tests the initial compaction states were selected to produce samples with high void ratio ($1.2 < e_0 < 1.57$) and low degrees of saturation ($0.4 < S_{r0} < 0.73$). In addition, samples with an initial height

Fig. 11. One-dimensional compression tests results with predicted data at constant degree of saturation (Al-Badran, 2011)

of 10 mm were used, as recommended by Campbell (1988) and Caruso & Jommi (2012), to reduce the drainage path and speed up the equilibration of pore-water volume change (suction) within the specimens.

The discussion contributors queried the loading rate adopted by the authors, and in response suggested that the net stress should be 'increased slowly' without further

Fig. 12. Compression results of Al-Badran (2011)

specific advice on how to select a suitable rate. The results of Al-Badran (2011) appear to be based on stepped loading with approximate doubling of the load between stages (see Fig. 12). Stepped loading generally applies the load ‘immediately’ (e.g. BSI, 1990). The results shown in Fig. 12 suggest that this procedure is quite difficult to ‘control’ as the loading step from approximately 100 kPa to 200 kPa appears to have exceeded the yield stress in test 30B-Sr58-com. At this point the degree of saturation jumps from about 48% to 58%. In contrast to the authors’ tests, prior to each loading step the degree of saturation was reduced (by increasing suction) so that after the application of the vertical stress increment the target degree of saturation was not exceeded (Al-Badran, 6 May 2014, personal communication). The authors believe that this change in S_r is significant, and that combined with the reduced S_r prior to loading, the tests do not follow constant S_r paths.

Equilibration curves for Speswhite kaolin specimens tested by Tripathy *et al.* (2014) and Baille (2014) are used by the discussion contributors to demonstrate the long testing

periods usually required for unsaturated soils. In the authors’ opinion, the comparison between the equilibration times is not straightforward. There is a lack of experimental data in the results presented by the discussion contributors during the early stages of drying to establish the equilibration time accurately. The first measurements were made after 1, 4 or 7 days. In addition, the samples of Tripathy *et al.* (2014) and Baille (2014), respectively, were prepared from slurry at initial water contents of $1.1w_L$ and $1.2w_L$, where w_L is the liquid limit. Reconstitution produced samples with substantially higher water content (60–66%) than the compacted specimens tested by the authors. This is reflected by the large reduction in water content of around 14 to 20% for an imposed suction of 0.05 MPa (Tripathy *et al.*, 2014).

In comparison, Fig. 13 shows the equilibration data measured in a compacted specimen (referred to as test OED22: $w_0 = 33.6\%$, $e_0 = 1.57$), first equilibrated to a suction of 10 kPa at a vertical net stress of 50 kPa. The sample was then subjected to drying (in steps) to a maximum suction of 300 kPa. The pore-water volume changes per step are small (Fig. 13(a)), from 250 mm³ to 1100 mm³, and similarly the water content changes (Fig. 13(b)) are also small compared to Tripathy *et al.* (2014). The equilibration for each change in suction is assessed to be achieved when 95% of pore-water inflow/outflow has occurred (Delage *et al.*, 2008) and ranges from 1.6 to 3.5 h as shown in Fig. 13(b).

The loading rate (12 kPa/h) employed during the constant S_r testing was selected taking into account evaporation from the sample (due to the low relative humidity imposed by the air pressure line) as well as air diffusion through the ceramic disc. Both of these affect the measured pore-water volume change and testing over long periods of time would make calculation of the water content (and S_r) problematic. Nevertheless, the equilibration during the constant S_r loading is evaluated using the analytical solution proposed by Kunze & Kirkham (1962). Based on this work, Delage *et al.* (2008) show that the time required to reach 95% equilibration of water inflow/outflow (t_{95}) can be approximately estimated as

$$t_{95} \approx 1.129 \frac{L^2}{D} \quad (4)$$

where L is the soil height and D is the capillary diffusivity coefficient. Equation (4) has been used to back-calculate the capillary diffusivity coefficient based on the equilibration (indicated by the arrows in Fig. 13(b)). As shown in Fig. 14(a), D reduces from 1.9×10^{-8} m²/s to 8.5×10^{-9} m²/s for suction increasing from 50 to 300 kPa,

Fig. 13. Equilibration data for drying at vertical net stress of 50 kPa in test OED22

Fig. 14. (a) Interpreted capillary diffusivity (D) for drying at vertical net stress of 50 kPa in test OED22 and (b) estimated variation of t_{95} for compacted kaolin specimens subjected to loading at constant S_r

Fig. 15. (a) Change in water volume and (b) suction during constant S_r loading for test OED19

Fig. 16. (a) Test OED22 stress path and (b) comparison of water retention behaviour

a similar range to that measured in the constant S_r testing. Fig. 14(b) shows the variation in the maximum ($t_{95\max}$) and minimum ($t_{95\min}$) time to equilibration based on the calculated D and the current sample height. The shaded area indicates the range of sample heights recorded during the tests and indicates that between 0.8 and 2.5 h would be required for the equilibration of pore-water volume for the range of suctions developed during the constant S_r testing.

Figure 15(a) shows the evolution of pore-water volume and Fig. 15(b) shows the evolution of suction in test OED19 during loading at constant S_r . The pore-water volume change during the loading to a vertical net stress of 1000 kPa is around 3500 mm³. This value is similar to the volume of pore-water expelled from specimen OED22 during drying from 100 to 300 kPa ($\delta V_w \approx 3500$ mm³, see Fig. 13(a)). The computed rates of pore-water volume change are shown in Fig. 15(a) to reduce from around 68 mm³/h to around 24 mm³/h. The rate of suction change, shown in Fig. 15(b), reduces from 5.6 kPa/h to 1.3 kPa/h. The pore-water volume and induced suction change shown in these figures are a consequence of the software control algorithm, which is set to maintain the condition of constant S_r . Combined with the above analysis, the low rates of both suction and water volume change seems to indicate that the selected loading rate was slow enough to allow equilibration of the pore-water volume during loading at constant S_r .

The full stress path followed in test OED22, discussed above, is shown in Fig. 16(a). The first drying path of the soil-water retention curve (SWRC) shown in Fig. 16(b) closely approximates that experienced by the tests during the constant S_r phases. The SWRC progressively moves to lower water contents for each drying–wetting cycle. This may be due to the progressive reduction in void ratio caused by previous loading and shrinkage of the specimen on drying. However, the SWRC obtained from OED22 shows a similar pattern of behaviour and matches well the results from the

constant S_r testing. As shown in Fig. 16(b), the comparison against SWRC available in the literature (Pineda *et al.*, 2008; Ikariya, 2009; Tarantino, 2011; Tripathy *et al.*, 2014) and additional samples tested by the authors, shows that the results from the S_r testing are suitable for justifying the performance of the proposed technique.

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